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Unconfounding the direction of motion in depth, time to passage and rotation rate of an approaching object

Rob Gray [a,*], David M. Regan [b]

[a] Department of Applied Psychology, Arizona State University, USA
[b] Department of Psychology, York University, Toronto, Canada

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Abstract

Observers were presented with a set of 216 simulated approaching textured baseballs in random order. In Experiment 1 each had a different combination of time to passage (TTP), direction of motion in depth (dMID) in the vertical plane and total change in angular size ($\Delta\theta$). In Experiments 2 and 3 each had a different combination of TTP, dMID and rate of ball rotation (RR). When required to discriminate TTP and dMID in separate experimental blocks for a non-rotating baseball (Experiment 1), observers could not discriminate dMID independently of variations in TTP but instead showed a bias towards perceiving objects approaching on a trajectory close to the nose as having a shorter TTP than objects approaching on a trajectory that would miss the face. When required to discriminate TTP, dMID and RR in separate experimental blocks (Experiment 2), TTP judgments were again influenced by dMID but could be made independently of RR. Judgments of the relative dMID were affected by variations in RR and rotation direction: for simulated overspin the (i.e., the top of the ball spins towards the observer) perceived ball trajectory was biased towards the ground whereas for simulated underspin the perceived ball trajectory was biased towards the sky. RR could be discriminated independently of both TTP and dMID. When required to make all three of these judgments simultaneously on each trial (Experiment 3) discrimination thresholds were not appreciably different from those found in Experiment 2. We conclude that TTP, dMID and RR can be estimated in parallel but not completely independently within the human visual system.

Keywords: Motion in depth; Time to passage; Vision and action

1. Introduction

How does an observer predict *where* an approaching object will be when it passes the fronto-parallel plane that contains the eyes? The dominant theory for many years has been that this judgment is based on retinal image variables that accurately specify the direction of motion in depth (angle β in Fig. 1A) and the passing distance (distance OP in Fig. 1A) of an approaching object (Beverley & Regan, 1973; Regan, Beverley, & Cynader, 1979). The specific variables are described in detail below. Recently, Harris and Drga (2005) have proposed an alternative account. These researchers argue that instead of using retinal image variables that accurately specify the object's trajectory, observers use the current visual direction of the approaching object (angle ϕ in Fig. 1A) to make a crude judgment of the direction it is traveling. As shown in Fig. 1B, trajectories with the same value of ϕ can have very different passing distances. Therefore, because visual direction does not accurately specify where the approaching object is headed, this account predicts that observers should make large systematic errors when judging the absolute direction of motion in depth (MID) for an approaching object. Although Harris and colleagues have provided some evidence for such judgment errors (Harris & Dean, 2003; Harris & Drga, 2005; Welchman, Tuck, & Harris, 2004), we have recently argued that these findings may be due to limitations associated with the methods used

* Corresponding author. Fax: +1 480 727 1538.
E-mail address: robgray@asu.edu (R. Gray).

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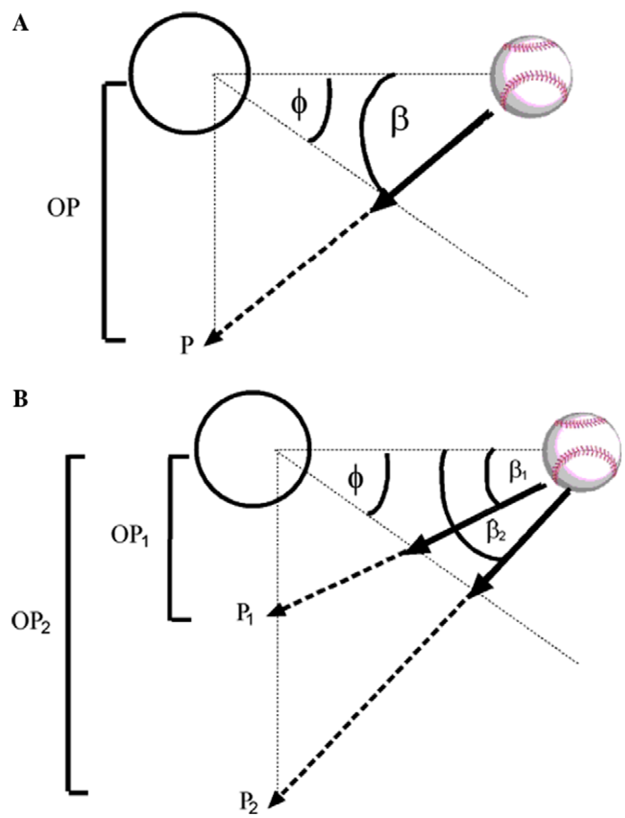

Fig. 1. Visual information that can be used to judge where an approaching object will pass the fronto-parallel plane that contains the eyes. (A) A spherical object is moving along the trajectory indicated by the arrows towards point P that is distance OP from the observer's eye (open circle). At time t the object will be located at the position indicated by the arrowhead of the solid line. Regan and colleagues have proposed that approach direction is judged on the basis of retinal image variables that accurately specify the angular direction of motion in depth (β) and passing distance (OP) while Harris and Drga (2005) have proposed that this judgment is based on the visual direction of the approaching object at time $t(\phi)$. (B) Visual direction does not accurately specify passing distance or direction of motion in depth. Two objects (one approaching point P_1 and one approaching point P_2) have a passing distance of OP_1 and OP_2, respectively. At time t the objects will be located at the positions indicated by the arrowheads of the solid lines. Even though these two objects have very different directions of motion in depth (β_1 and β_2) and passing distances they will have the same visual direction at time t (ϕ).

to measure perceived direction of MID and insufficient stimulus variation (Gray, Regan, Castaneda, & Sieffert, 2006). Furthermore, using a methodology that addressed these issues we showed that observers can make accurate estimates of the absolute direction of MID of an approaching object consistent with the original hypothesis of Regan and colleagues.

Regardless of what visual information is used, there are two important requirements for accurate estimation of approach direction that have often been overlooked in past research. First, the observer must be able judge where the object is headed *independently* of other stimulus variables. For example, β and OP in Fig. 1A must be judged independently of the speed of the approaching object and *when* the object will pass the fronto-parallel plane that contains the eyes [called the time to passage (TTP)]. This may sound like a somewhat trivial issue however past research has identified several situations in which judgments of TTP [or time to collision (TTC)][1] cannot be made independently of other stimulus variables including the object's velocity (Kerzel, Hecht, & Kim, 1999), angular size (Delucia, 1991), relative depth (DeLucia, Kaiser, Bush, Meyer, & Sweet, 2003) and the rate and direction of optic flow produced by self-motion (Gray, Macuga, & Regan, 2004). Therefore, it would seem reasonable to expect that judgments of approach direction cannot be made completely independently of other stimulus variables. A second requirement is that the observer must be able to make judgments of approach direction in *parallel* with judgments of other task-relevant variables, such as TTP. Parallel processing is necessary in this situation because of the severe time constraints involved in many interceptive actions, e.g., for professional baseball it has been estimated that batters have less than 0.3 s to process information about TTP and direction of MID (Bahill & Karnavas, 1993).

Unfortunately, neither of these requirements has been addressed in past research because psychophysical studies of MID [reviewed in Regan and Gray (2000)] have been restricted to discriminating either trial-to-trial variations in the direction of MID or trial-to-trial variations in TTP (or TTC), and did not address how well simultaneous variations in the two quantities could be unconfounded and discriminated. The purpose of the present study was to investigate to what extent the direction of MID of an approaching object could be judged *independently* and in *parallel* in the human visual system. We next describe the specific retinal image variables that were investigated in this study.

1.1. Visual correlates of where and when for an approaching sphere

Monocularly available correlates of *where* an approaching object will pass the fronto-parallel plane that contains the eyes have been derived mathematically. Fig. 2 illustrates the case of a ball approaching point P that is a distance OP below the observer's eyes. In this case β, the direction of motion in depth (MID), is given by Eq. (1)

$$\beta \approx \tan^{-1} \frac{2R(\mathrm{d}\phi/\mathrm{d}t)}{D(\mathrm{d}\theta/\mathrm{d}t)}, \tag{1}$$

where $\mathrm{d}\phi/\mathrm{d}t$ is the angular vertical velocity of the approaching object, $\mathrm{d}\theta/\mathrm{d}t$ is its rate of change of angular subtense, D is its distance from the eye and R its radius (Bootsma, 1991; Regan & Kaushal, 1994). It follows from Eq. (1) that the distance from the centre of the pupil of the

[1] Throughout this paper we will follow the convention of referring to the time remaining until an approaching object reaches the eye as the time to collision (TTC) and the time remaining until an approaching object not on a direct approach with eye crosses the fronto-parallel plane containing the eyes as the time to passage (TTP).

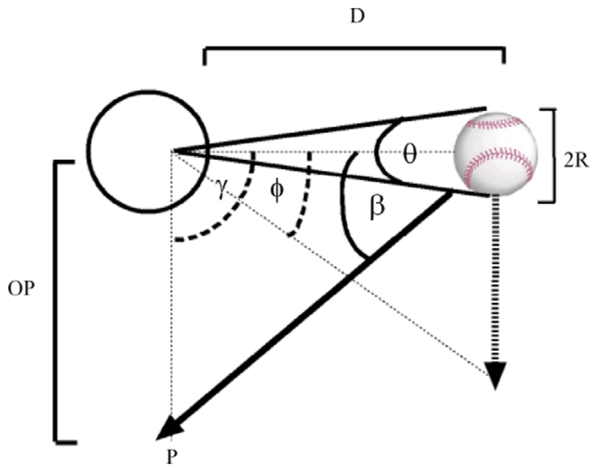

Fig. 2. Visual information about the direction of motion in depth (MID) and time to passage (TTP) of an approaching object. A ball radius R travels at a constant speed along a straight line (shown by the heavy arrow) towards point P which is distance OP below the observer's eye. Its instantaneous distance from the observer's is eye (open circle) is D. θ is the ball's instantaneous angular subtense, γ is the optical angle at the eye subtended by the current location of the ball and point P and ϕ is the angular change in its vertical position (or visual direction). β is the angular direction of MID relative to the midline.

observing eye to the interception point (P) in Fig. 2 (i.e., the passing distance) is given by

$$\mathrm{OP} \approx \frac{2R(\mathrm{d}\phi/\mathrm{d}t)}{\mathrm{d}\theta/\mathrm{d}t}. \tag{2}$$

As discussed above, the most obvious stimulus variable that must be judged independently and in parallel with the approach direction is the TTP of the approaching object. A retinal image correlate of the time to collision (TTC) with a rigid sphere that is moving directly towards the observing eye at constant speed is expressed in Eq. (3)

$$\mathrm{TTC} \approx \frac{\theta}{(\mathrm{d}\theta/\mathrm{d}t)}, \tag{3}$$

where θ is the instantaneous angular subtense of the approaching object and θ is the small (Hoyle, 1957; Lee, 1976). It follows that the time to passage (TTP) for an object approaching a point some distance from the observer's eyes as shown in Fig. 2 is given by Eq. (4)

$$\mathrm{TTP} = \frac{\mathrm{TTC}}{\cos^2\beta} \tag{4}$$

so that if β is small TTP $\approx$ TTC. For example, if $\beta = 10$ deg, the error is ca. 3%. For large values of β, Eq. (5) gives a more exact value than is given by Eq. (4) for the time taken for an object moving at constant speed along a straight line to travel from its current position to a point P that does not coincide with the observing eye (e.g., the observer's hand)

$$\mathrm{TTP} \approx \frac{2(\theta/\mathrm{d}\theta/\mathrm{d}t)}{1 + 2(\mathrm{d}\beta/\mathrm{d}t)(\gamma/\mathrm{d}\gamma/\mathrm{d}t)\cos\theta}, \tag{5}$$

where γ is the optical angle at the eye subtended by the current location of the ball and point P, $\mathrm{d}\gamma/\mathrm{d}t$ is the rate of constriction of this angle, and β is the ball's direction relative to the observer's eye (Tresilian, 1990).

One point that needs to be discussed further is that there is an inherent link between the visual correlates of TTP and approach direction. Namely, the visual correlate of approach direction (β) appears in the equations for TTP. Therefore, in one sense the processing of TTP information cannot be completely independent of the processing of approach direction information: processing of β is necessary for the estimation of TTP. However, this link does not necessarily imply that there will be a lack of independence at the judgment stage—the primary interest of the present study. Independence at the judgment stage occurs when an observer can make accurate estimates of TTP despite variations in the approach direction. An example, of dependence at the judgment stage would be if TTP were overestimated (i.e., perceived to be longer than it actually is) when the approach angle β was larger. Since β is part of a complex ratio in Eq. (5) an increase in approach direction would not necessarily lead to an increase in perceived TTP, i.e., a change in approach direction would change the value of β but would also change the value of γ in Eq. (5). See Regan and Hamstra (1993) for further discussion of this issue.

1.2. Approach direction, object rotation and the Magnus Effect

A less obvious variable that might influence judgments of the direction of MID of an approaching object is visual information about object rotation. In everyday life there is a relationship between object rotation and the direction of MID caused by the *Magnus Effect* [Magnus, cited in Rayleigh (1869–1881)].[2] If a horizontally moving ball spins about a vertical axis, one side of the ball has a higher horizontal speed than the other. Consequently, the ball experiences a horizontal force perpendicular to its direction of motion that causes it to curve through its flight as shown in Figs. 3C and D. If a horizontally moving ball spins about a horizontal axis perpendicular to its direction of motion, the Magnus force will either add to the force of gravity in the case of overspin (Fig. 3E) thus causing the trajectory to curve more strongly downwards, or oppose the force of gravity in the case of underspin (Fig. 3F) thus causing the trajectory to be flatter than would have been the case for a non-rotating ball. In sports such as baseball it has been demonstrated that players can use the motion of the surface texture

[2] A formal treatment of the aerodynamics of a moving sphere is provided by Landau and Lifshitz (1959). The Magnus effect in its relation to baseball is discussed by Briggs (1959), Adair (1990) and Watts and Bahill (1991). The physics of the Magnus effect in its relation to golf discussed by Davies (1949) and Erlichson (1983), in relation to cricket by Mehta and Wood (1980) and in relation to tennis by Rayleigh (1869–1881). A general discussion of the Magnus effect and ballgames is provided in Appendix 2 to Regan (1992).

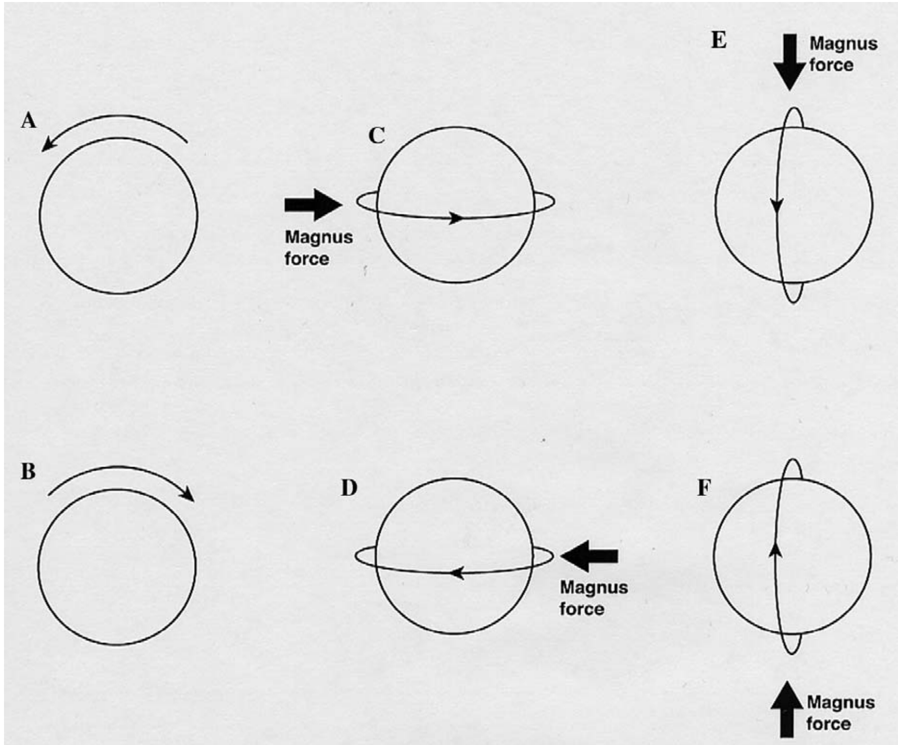

Fig. 3. The spin of a ball can be resolved into three orthogonal components. An approaching ball is shown from the batter's viewpoint. The three components of rotation are shown as (A and B), (C and D), and (E and F). The rotation component shown in (C and D) creates a Magnus force that causes to ball's trajectory to curve leftwards or rightwards. The rotation component shown in E and F creates a Magnus force that either assists (E) or opposes (F) gravity.

(i.e., the laces) to accurately judge the direction of object rotation (Burroughs, 1984) and that players can use this information to predict the future location of the ball (Gray, 2002). Therefore, since there is a physical relationship between approach direction and object rotation, it is interesting to ask whether these two variables are also linked perceptually. This issue has not been addressed in past research since the vast majority of psychophysical studies on judgments of approach direction have used un-textured objects [reviewed in Regan and Gray (2000)].

In addition to the Magnus Effect there is another link between approach direction and object rotation. As discussed in detail by Tresilian (1991), when a non-rotating, textured object has an off-axis approach there will be an apparent rotation of the object due to motion of the surface texture. For example, if an object has an approach angle of 15 deg relative to the midline and a TTP of 1.0 s the apparent rotation rate will be roughly 1 deg/s. In baseball rotation rates typically exceed 9000 deg/s (Watts & Bahill, 1991). Even for knuckleball, which a pitcher tries to throw with as little rotation as possible, rotation rates are roughly 180–300 deg/s (Watts & Bahill, 1991). Therefore, it is unlikely that the small apparent rotation rate associated with an off-axis approach would affect judgments of rotation rate in most situations. This prediction is tested empirically in Experiment 2 below.

1.3. Aims of the present study

In the present study, we used a simulated approaching textured object (a baseball) that varied in the direction of MID, TTP, rotation rate and rotation direction. In Experiment 1, we investigated to what extent judgments of the direction of MID could be made independently of variations in the object's TTP. In Experiment 2, we investigated to what extent judgments of the direction of MID and TTP could be made independently of variations in the object rotation rate and rotation direction. In particular, we were interested in whether or not direction of MID judgments would incorporate the Magnus Effect illustrated in Fig. 3 (i.e., would observers judge an approaching object traveling with overspin as having a trajectory closer to the ground than an approaching object traveling with underspin?). Finally in Experiment 3, we investigated whether judgments of MID, TTP and object rotation rate could be made in parallel in the human visual system.

2. Experiment 1

2.1. Purpose

The purpose of Experiment 1 was to measure Weber fractions for the discrimination of TTP and the discrimination of the direction of MID when the observer was making a single judgment (i.e., either TTP or direction) on each trial and the simulated ball did not rotate. These baseline data were then compared to the data from Experiments 2 and 3 in which observers made multiple simultaneous judgments and ball rotation was added.

2.2. Method

2.2.1. Apparatus

A simulated approaching baseball was used. The ball, generated using OpenGL, was an off-white sphere texture mapped with red laces and was displayed on an 28 cm vertical × 36 cm horizontal SVGA monitor (Viewsonic model PT795) that ran at 120 Hz. The background was black. The monitor was viewed monocularly from a distance of 80 cm in a dark room. The initial vertical position of the simulated ball (i.e., at time $t = 0$) was always 10 deg above the center of the display. The initial angular radius of the ball was 5 deg. A sensation of motion towards the observer was created by increasing the angular size of the ball. The rate of downward movement of the simulated ball was varied to create different trajectories of motion in depth within the vertical plane. The horizontal position of the simulated ball remained constant. Specifically, different trajectories of MID were created by changing the angular size of the ball as a function of time (θ_t) according to:

$$\theta_t = \tan^{-1}\left(\frac{\tan\theta_0}{1 - t/\mathrm{TTP} * \cos^2\beta}\right) \tag{6}$$

and by changing the vertical angular position of the ball as a function of time (α_t) according to:

$$\alpha_t = \frac{X_c(\theta_t - \theta_0)}{2(\tan\theta_0)D}. \tag{7}$$

The orientation of the ball at time $t = 0$ was randomized so that the position of the laces did not provide a reliable cue to the direction of MID or TTP.

2.2.2. Procedure

Psychometric functions for discriminating trial-to-trial variations in the TTP and direction of MID were measured using the method of constant stimuli combined with two-interval forced choice. Each trial consisted of two presentations of a simulated approaching object: A "test target" and a "reference target". The values of TTP (i.e., Eq. (5)) and β (i.e., Eq. (1)) for the test target were chosen randomly from a $6 \times 6 \times 6$ orthogonal stimulus array that can be conceptualized as a cube. Within this stimulus cube, TTP was varied along the x-axis, direction of MID was varied along the y-axis and the total change in object size ($\Delta\theta$) was varied along the z-axis. The value of $\Delta\theta$ was varied by adjusting the presentation duration. The 216 stimuli were presented in random order. See Portfors-Yeomans and Regan (1997) for further details about this design. The six TTP values used were 0.75, 0.85, 0.95, 1.05, 1.15 and 1.25 s. The six values of the angle β used were 2, 4, 6, 8, 10 and 12 deg below line of sight. The six values of $\Delta\theta$ used were 2, 2.2, 2.4, 2.6, 2.9 and 3.3 deg. The values of TTP, direction of MID and $\Delta\theta$ for the reference target were always the mean of the stimulus set, i.e., TTP = 1.0 s and $\beta = 7$ deg. The presentation duration of the "reference target" was always the same as the duration for the "test target". Presentation durations ranged between 0.4 and 0.66 s (depending on the value of $\Delta\theta$). The order of presentation for the test and reference targets was chosen randomly on each trial. For the TTP discrimination task, observers were instructed to indicate in which presentation the object would have passed the frontal plane containing their eyes later by pressing one of two response buttons. When discriminating the direction of MID, observers were instructed to indicate in which presentation the object would have passed nearer to their eyes by pressing one of two response buttons. The inter-stimulus interval was 300 ms and the inter-trial interval was 1 s.

Each run consisted of one presentation of each of the 216 stimuli. All observers completed 10 runs for the TTP discrimination task and 10 runs when discriminating the direction of MID. The order of these two tasks was counterbalanced across observers. No response feedback was given.

2.2.3. Data analysis

For each task we constructed three separate psychometric functions by collapsing the data onto each of the axes of the stimulus cube. For example, for the TTP discrimination task we separately plotted the percentage of "TTP of test longer than the reference" responses as a function of the values TTP, β and $\Delta\theta$ for the test stimulus. Each of these curves was based on of 360 data points. These data were submitted to probit analysis (Finney, 1971) and the resultant curve fits were used to calculate discrimination thresholds. Discrimination thresholds were defined as $0.5 * (V_{75}–V_{25})$ where V_{75} and V_{25} were, respectively, the values of each variable (i.e., TTP, β or $\Delta\theta$) for 75% and 25% "TTP of test longer than the reference" responses. An analogous procedure was used for the "direction of MID" discrimination task. This analysis allowed us to determine to what extent observers could discriminate the TTP of the approaching object while ignoring simultaneous variations in β and $\Delta\theta$ and to what extent observers could discriminate the value of β for the approaching object while ignoring simultaneous variations in TTP and $\Delta\theta$.

2.2.4. Observers

Four observers completed Experiment 1. All observers had 6/6 or corrected to 6/6 visual acuity, normal results on the acuity, binocular vision, color vision and phoria tests of the Optec Vision Tester (Stereo Optical Co., Inc., Chicago, IL). All four observers were naïve as to the aims of the experiment and performed the experiment for course credit.

2.3. Results

2.3.1. TTP discrimination

Fig. 4 plots the percentage of "TTP of test longer than the reference" responses as a function of TTP (Fig. 4A), β (Fig. 4B) and $\Delta\theta$ (Fig. 4C) for observer 1. To allow for comparison between these functions we expressed all variables as a fractional departure from the value of reference (i.e., TTP_{TEST}/TTP_{REF}). It is clear from the steep function in Fig. 4A that this observer could reliably discriminate TTP. The Weber fraction in Fig. 4A was 0.13. Contrast this with the almost-flat function in Fig. 4C with a Weber fraction of −2.4, about 18 times larger than in Fig. 4A.[3] Clearly, observer 1 could almost completely ignore variations in the value of $\Delta\theta$ when discriminating TTP. It can also be seen in Fig. 4 that when discriminating TTP the judgments of observer 1 were slightly influenced by the direction of MID: TTP was perceived to be longer for larger values of β. The Weber fraction in Fig. 4B was 0.44, about 3 times larger than in Fig. 4A. Similar results were obtained for the other three observers. Weber fractions for these observers are shown in Table 1.

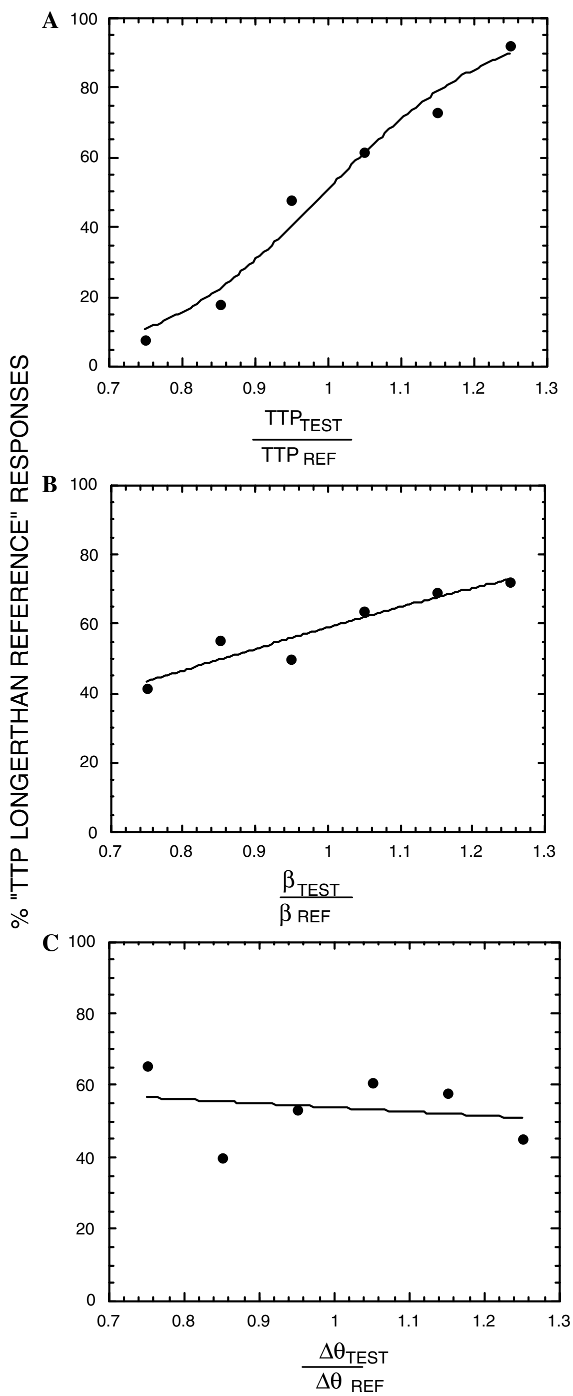

Fig. 4. Psychometric functions for Time to Passage (TTP) discrimination in Experiment 1. The percentage of "TTP of test longer than the reference" responses is plotted as a function of TTP (A), β (B) and $\Delta\theta$ (C). To allow for comparison between these functions we expressed all variables as a fractional departure from the value of reference (see text for details). Solid lines are best fitting probit functions.

Table 1
Discrimination thresholds for TTP judgment in Experiment 1

Observer	TTP	β	$\Delta\theta$
1	0.13	0.44	−2.4
2	0.15	0.51	1.87
3	0.22	0.61	−2.2
4	0.18	0.33	1.5

2.3.2. Discrimination of the direction of MID

Fig. 5 plots the percentage of "Test stimulus passed further from the eye than the reference" responses as a function of TTP (Fig. 5A), β (Fig. 5B) and $\Delta\theta$ (Fig. 5C) for observer 1. In this figure it can be seen that this observer could discriminate trial-to-trial variations in the direction of MID (threshold = 0.12) while almost entirely ignoring simultaneous variations in TTP (threshold = 7.2) and $\Delta\theta$ (threshold = −1.8). Similar results were obtained for the other three observers. Weber fractions for these observers are shown in Table 2.

2.4. Discussion

In Experiment 1, we measured the precision of discriminating both TTP and the direction of MID in the case

[3] This ratio quantifies the confidence with which we may conclude that an observer based the discrimination on the task-relevant variable and ignored the particular task-irrelevant variable. In previous reports we have found that ratios can vary from less than 1.0 (the observer was more influenced by the task-irrelevant than by the task-relevant variable) to more than 30 (Gray & Regan, 1998; Kohly & Regan, 1999; Portfors-Yeomans & Regan, 1996; Regan & Hamstra, 1993) and that the ratio can be altered tenfold by only a small change in stimulus parameters and this without the observer's being aware of a change in response strategy (Kohly & Regan, 1999; Portfors-Yeomans & Regan, 1996). However, it is commonly not possible to distinguish between a low slope and a zero slope and there is no ratio for which the observer can be said to totally ignore a task-irrelevant variable. Rather, there is a continuous transition from <1.0 to a high ratio (Kohly & Regan, 1999). As a working assumption we take ratios above about 10 to signal that the observer was effectively uninfluenced by the task-relevant variable.

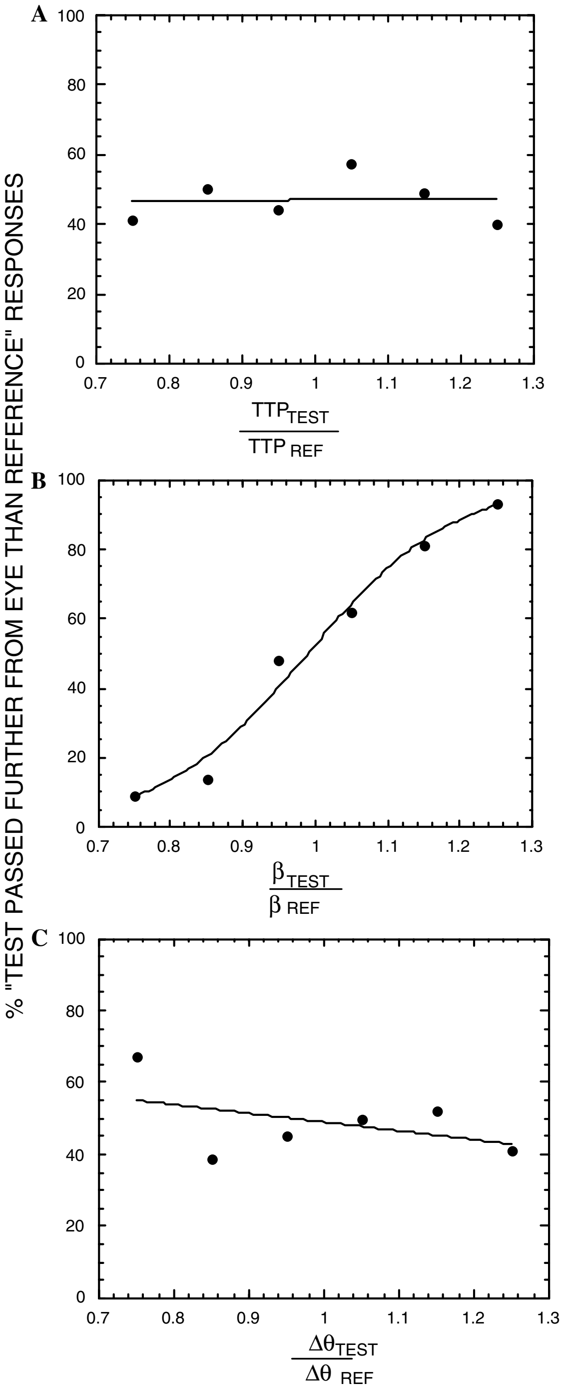

Fig. 5. Psychometric functions for direction of motion in depth (MID) discrimination in Experiment 1. The percentage of "test stimulus passed further from the eye than the reference" responses are plotted function of TTP (A), β (B) and $\Delta\theta$ (C). To allow for comparison between these functions we expressed all variables as a fractional departure from the value of reference (see text for details). Solid lines are best fitting probit functions.

where observers were required to make a single judgment on each trial. For TTP, Weber fractions were relatively low (ranging from 0.13 to 0.22). Since the mean value of TTP used in the present study was 1.0 s these values correspond to thresholds of roughly 120 to 220 ms. These values

Table 2
Discrimination thresholds for direction of MID judgment in Experiment 1

Observer	TTP	β	$\Delta\theta$
1	7.2	0.12	−1.8
2	2.7	0.13	3.2
3	3.6	0.19	−2.8
4	2.1	0.11	2.8

are slightly higher than the 0.05–0.13 Weber fractions for judgments of TTC found in previous research for objects directly approaching the midpoint between the eyes (Regan & Hamstra, 1993;Todd, 1981). Part of the reason for the higher thresholds found in the present study may be that our observers could not judge relative TTP completely independently of the direction of MID: For all observers there was consistent bias towards perceiving objects approaching on a trajectory close to the nose as having a shorter TTP than objects approaching on a trajectory that would miss the face even when both objects had the same TTP. This could be thought of as an ecologically advantageous "hitting the head bias", i.e., it would be advantageous if the initial estimate of TTP were shorter when an object was on a collision course with the head because it would allow more time for collision avoidance. Qualitatively this bias is similar to the consistent bias towards underestimating absolute TTC [reviewed in (Regan & Gray, 2000)] and to the increase in TTC underestimation during forward self-motion (Gray et al., 2004; Gray & Regan, 2000b).

Weber fractions for monocular correlates of the direction of MID were also low for our observers (ranging from 0.11 to 0.19). Furthermore, our observers could discriminate the direction of MID almost independently of TTP. For the 7 deg mean value of β used in the present study these Weber fractions correspond to thresholds of roughly 0.7–1.3 deg. These are again higher than the 0.1 deg thresholds reported by Regan and Kaushal (1994). The higher thresholds found in the present study may be due to the fact we varied TTP and used a much wider range of approach trajectories. Not surprisingly, it has been shown that the sensitivity to motion in depth information falls off dramatically for objects that are on an approach trajectory that will not collide with the observer's head (Regan et al., 1979).

3. Experiment 2

3.1. Purpose

In Experiment 2, we simulated a rotating ball. The purpose of Experiment 2 was to measure thresholds for the discrimination of TTP, direction of MID and rotation rate when the observer was making a single judgment on each trial. As discussed above, in the real-world the rotation rate and rotation direction influence both the actual trajectory of MID of a baseball (Briggs, 1959) and batting performance (Gray, 2002). Therefore, we investigated whether these variables also influence the perceived trajectory of MID. An additional aim of Experiment 2 was to quantify the discrimination of object rotation rate. Although it has been shown that human observers can utilize this visual information (Burroughs, 1984; Gray, 2002) to our knowledge rotation rate discrimination thresholds have not been measured in previous research.

3.2. Method

3.2.1. Apparatus and procedure

The apparatus and procedure were identical to that described for Experiment 1 except that the simulated ball rotated as it approached the observer. We again used a $6 \times 6 \times 6$ orthogonal stimulus array but in Experiment 2 we varied the rate of ball rotation ($d\eta/dt$) along the z-axis of the stimulus array. The same six values of TTP and the same six values of β described for Experiment 1 were again used. The six values of $d\eta/dt$ were 2700, 3060, 3420, 3780, 4140 and 4500 deg/s. These rotation rates (corresponding to a range of 450–750 rpm) are considerably slower than the rotation rates typically observed in major league baseball that range from 1000 to 1900 rpm (Watts & Bahill, 1991). This was necessitated by the frame rate of our display. In separate experimental blocks we simulated overspin (Fig. 3E) and underspin (Fig. 3F). The presentation duration was randomly varied between 0.4 and 0.7 s to partially dissociate $\Delta\theta$ from the task-relevant variables. Note that we did not simulate the Magnus Effect in our display so that unlike the real-world case the simulated rotation did not actually effect the direction of MID.

Observers performed six experimental blocks: (i) TTP discrimination, overspin, (ii) discrimination of the direction of MID, overspin, (iii) spin rate discrimination, overspin, (iv) TTP discrimination, underspin, (v) discrimination of the direction of MID, underspin and (vi) rotation rate discrimination, underspin. For the rotation rate discrimination observers indicated which presentation had a faster rotation rate by pressing one of two response buttons. Each run consisted of one presentation of each of the 216 stimuli presented in random order and each block comprised three runs. The order in which the six blocks were completed was counterbalanced across observers.

3.2.2. Observers

The same four observers completed Experiment 2.

3.3. Results

3.3.1. TTP discrimination

Fig. 6 plots the percentage of "TTP of test longer than the reference" responses as a function of TTP (panels A and D), β (panels B and E) and $d\eta/dt$ (panels C and F) for observer 1. Panels A–C are for simulated overspin and panels D–F are for simulated underspin. Solid lines show best fitting probit functions. Each of these functions was based on 108 data points. Weber fractions were calculated as described for Experiment 1. It is clear from the steep function in Figs. 6A and D that this observer could reliably discriminate TTP: the Weber fractions were 0.11 and 0.13, respectively. As was the case in Experiment 1, we found a small effect of β on TTP discrimination (as shown in Figs. 6B and E). Thresholds in these figures were 0.34 and 0.54, respectively, about 3 and 4 times larger than in Figs. 6A and D, respectively. Finally, from the almost-flat functions in Figs. 6C and F it is clear that neither rotation rate nor rotation direction influenced judgments of relative TTP. Weber fractions in Figs. 6C and F were −4.0 and 2.0, respectively. As shown in Table 3 similar results were obtained for the other three observers.

3.3.2. Discrimination of the direction of MID

Fig. 7 plots the percentage of "Test stimulus passed further from the eye than the reference" responses as a function of TTP (panels A and D), β (panels B and E) and rotation rate (panels C and F) for observer 1. Panels A–C are for simulated overspin and panels D–F are for simulated underspin. It is clear from the steep functions in Figs. 7B and E that this observer could reliably discriminate the direction of MID: The Weber fractions in Figs. 7B and E were 0.1 and 0.11, respectively. Furthermore, the almost-flat functions in Figs. 7A and C indicate that this observer could almost entirely ignore trial to trial variations in TTP when judging the direction of MID. This is consistent with the findings of Experiment 1. The Weber fractions in Figs. 7A and C were 3.4 and −2.9, respectively. As shown in Table 4 similar results were obtained for the other four observers.

We next turn to an examination of the effects of rotation rate and rotation direction on judgments of the relative direction of MID. It is clear from Figs. 7C and F that these two variables influenced judgments of the direction of MID for observer 1. As shown in Fig. 7C, for the overspin condition an increase in the rotation rate lead to an *increase* in the % of "trajectory further from the nose" responses whereas for the underspin condition (Fig. 7F) an increase in rotation rate lead to a *decrease* in the % of "trajectory further from the nose" responses". The Weber fractions in Figs. 7C and F were 0.28 and −0.35, respectively, about three times larger than in Figs. 7B and E. As shown in Table 4 similar results were obtained for the other three observers.

3.3.3. Rotation rate discrimination

Fig. 8 plots the percentage of "Test stimulus rotated faster than the reference" responses as a function of TTP (panels A and D), β (panels B and E) and rotation rate (panels C and F) for observer 1. Panels A–C are for simulated overspin and panels D–F are for simulated underspin. It is clear from the steep functions in Figs. 8C and F that this observer could reliably dis-

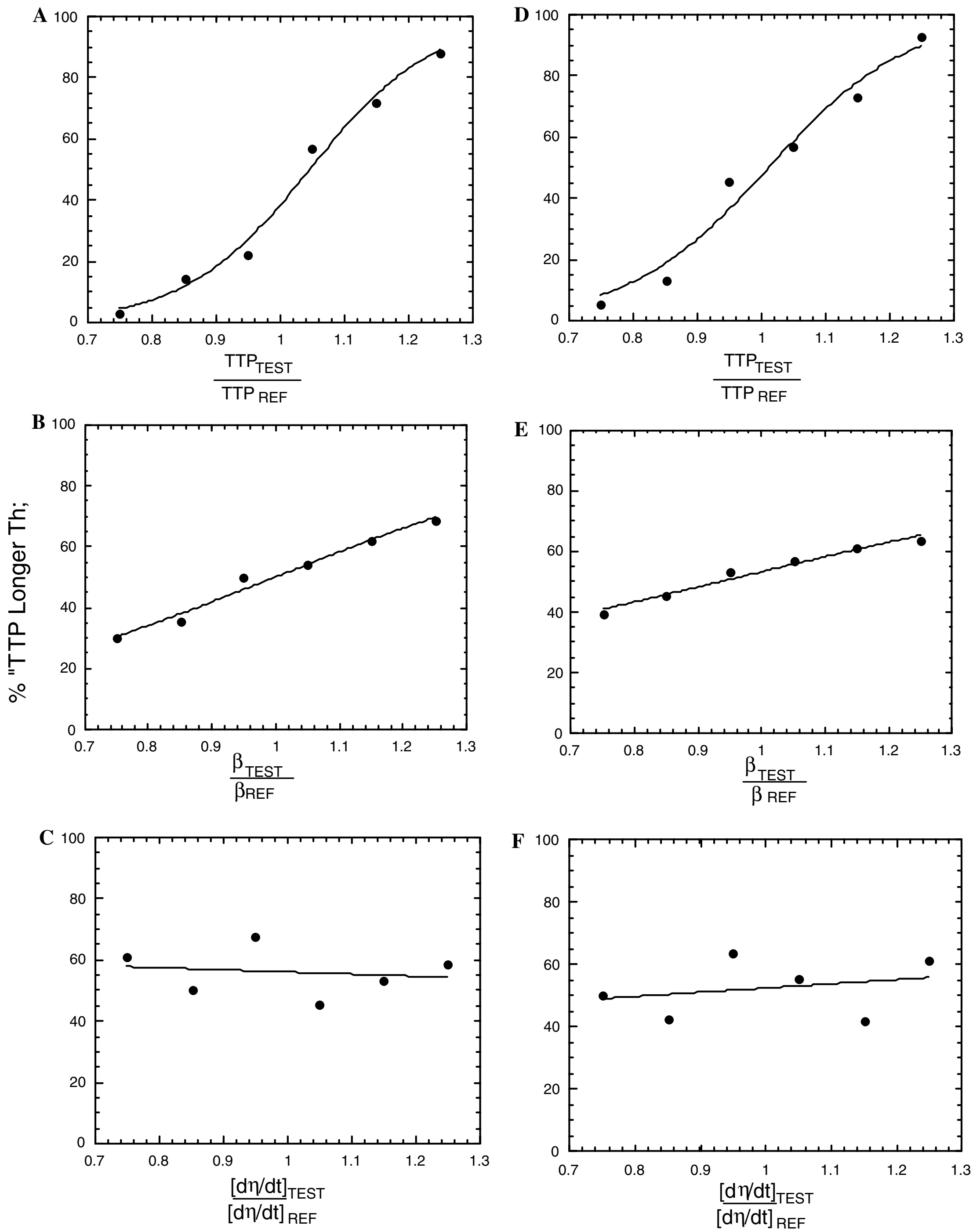

Fig. 6. Psychometric functions for TTP discrimination in Experiment 2. The percentage of "TTP of test longer than the reference" responses is plotted as a function of TTP (A and D), β (B and E) and $d\eta/dt$ (C and F) for observer 1; (A–C) are for simulated overspin and (D–F) are for simulated underspin. Solid lines show best fitting probit functions.

Table 3
Discrimination thresholds for the TTP judgment in Experiment 2

Observer	TTP, over	β, over	$d\eta/dt$, over	TTP, under	β, under	$d\eta/dt$, under
1	0.11	0.34	−4.0	0.13	0.54	2.0
2	0.14	0.52	−2.32	0.12	0.40	1.5
3	0.18	0.39	−1.7	0.20	0.51	3.4
4	0.09	0.61	3.1	0.11	0.39	−5.4

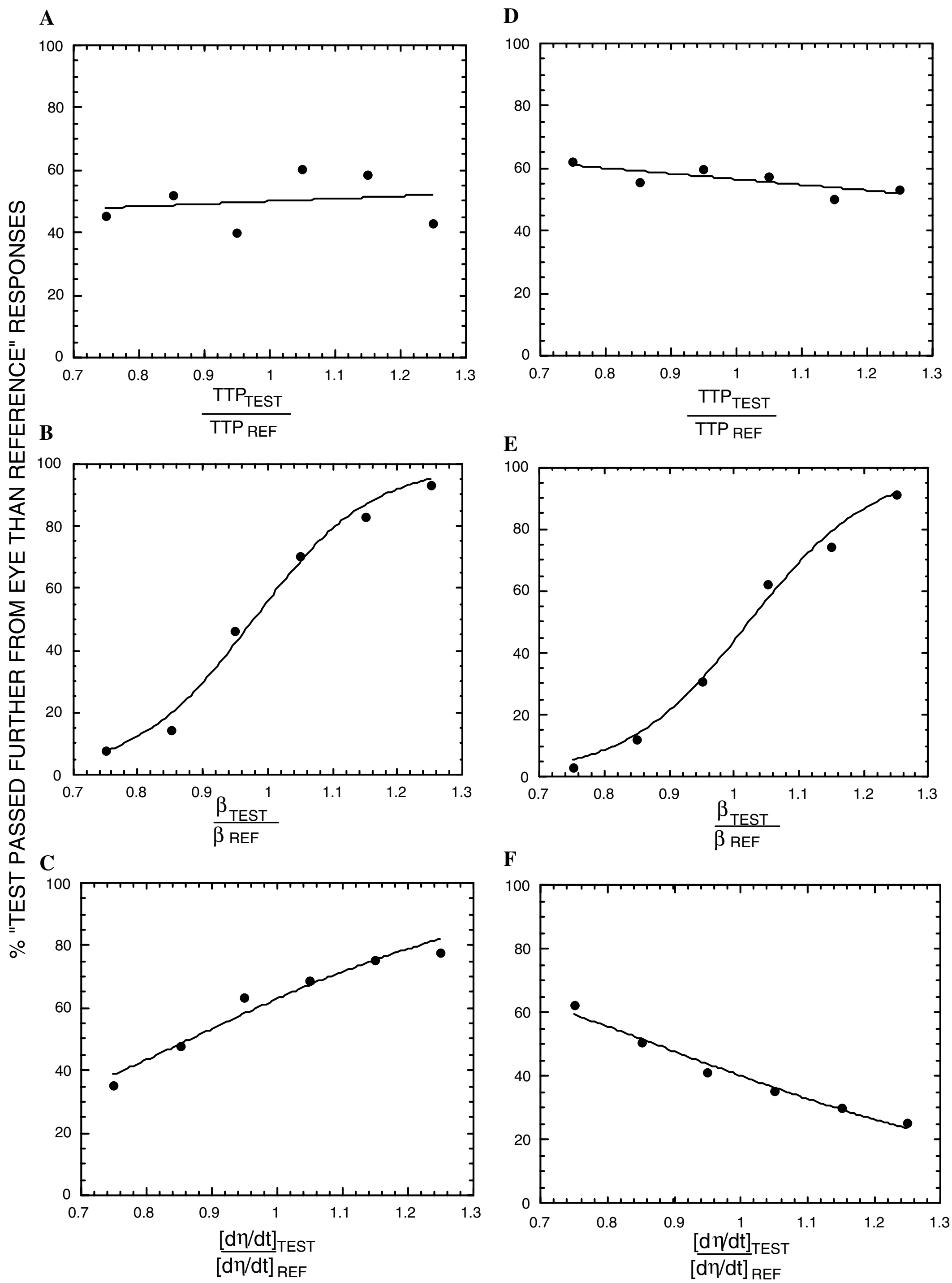

Fig. 7. Psychometric functions for direction of MID discrimination in Experiment 2. The percentage of "Test stimulus passed further from the eye than the reference" responses is plotted as a function of TTP (A and D), β (B and E) and $d\eta/dt$ (C and F) for observer 1; (A–C) are for simulated overspin and (D–F) are for simulated underspin. Solid lines show best fitting probit functions.

Table 4
Discrimination thresholds for the direction of MID judgment in Experiment 2

Observer	TTP, over	β, over	$d\eta/dt$, over	TTP, under	β, under	$d\eta/dt$, under
1	3.4	0.10	0.28	−2.9	0.11	−0.35
2	8.7	0.19	0.42	4.6	0.21	−0.32
3	12.2	0.12	0.29	12.2	0.14	−0.50
4	−4.8	0.17	0.33	−7.7	0.19	−0.38

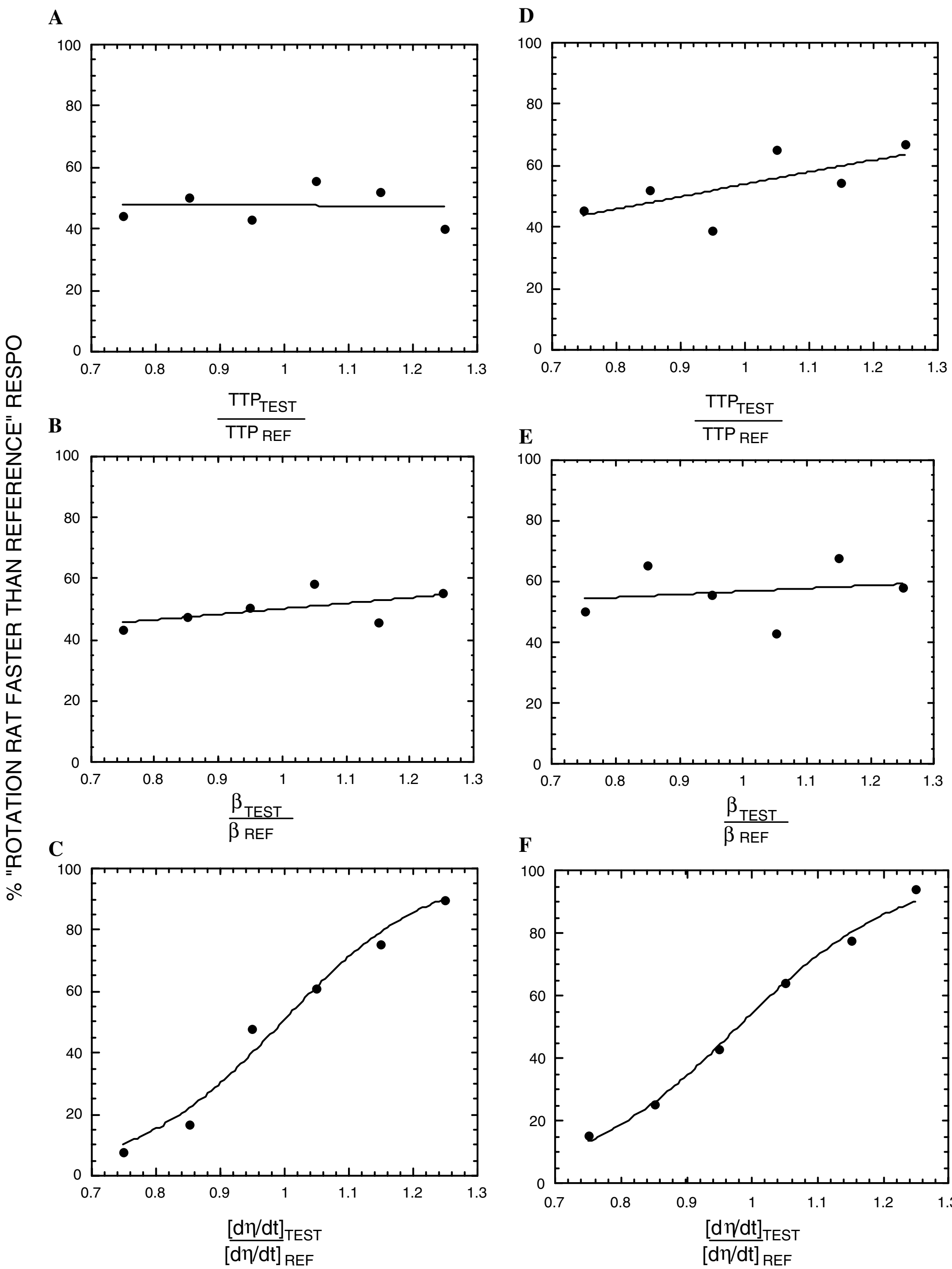

Fig. 8. Psychometric functions for rotation rate discrimination in Experiment 2. The percentage of "Test stimulus rotated faster than the reference" responses is plotted as a function of TTP (A and D), β (B and E) and dη/dt (C and F) for observer 1; (A–C) are for simulated overspin and (D–F) are for simulated underspin. Solid lines show best fitting probit functions.

criminate the rotation rate for both overspin and underspin: the Weber fractions in Figs. 8C and F were both 0.13. From the almost-flat functions in Figs. 8A and D it appears that this observer could judge rotation rate effectively independently of TTP and from the almost-flat functions in Figs. 8B and E it appears that this observer could judge rotation rate effectively independently of β. This later finding is consistent with our prediction described above that the apparent rotation of an approaching object produced by an off-axis approach would not affect judgments of RR when the actual rotation rate of the approaching object is large. Similar results were obtained for the other three observers as shown in Table 5.

Table 5
Discrimination thresholds for the rate of rotation judgment in Experiment 2

Observer	TTP, over	β, over	$d\eta/dt$, over	TTP, under	β, under	$d\eta/dt$, under
1	−12.7	1.6	0.13	0.74	2.8	0.13
2	2.5	2.2	0.20	2.5	−10.7	0.21
3	3.3	1.8	0.18	−3.3	8.8	0.15
4	−5.6	5.6	0.14	4.7	−6.6	0.17

3.4. Discussion

In everyday-world situations such as driving, flying or playing sports, observers must often avoid a collision with an object which appears to rotate because of the observer's trajectory or create a collision with an object that is rotating as it approaches. We have previously shown that for rotating non-textured and nonspherical objects estimates of TTC can be inaccurate when based on monocular information alone (i.e., Eq. (3))(Gray & Regan, 2000a). This occurs because the rotation causes the object's retinal image to change shape as it expands (Regan & Beverley, 1979). In the present study, we extended this previous finding by examining the effect of object rotation on the discrimination of both TTP and the direction of MID for a simulated spherical textured object (a baseball). We report that rotation direction and rate did not affect discriminations of TTP for a simulated spherical object consistent with our previous findings on judgments of TTC (Gray & Regan, 2000a). However, the rotation direction and rotation rate did affect the perceived direction of MID. The error in the perceived direction of MID was in the direction that the Magnus Effect acting on a real approaching object would have changed the object's actual direction of MID.

It has been previously shown that the rotation direction and rotation rate can be used by experienced baseball players to aid judgments of both pitch speed and the height the ball will be when it crosses the plate (Gray, 2002). However observers' sensitivity to rotation rate has not been systematically measured in previous research. Here, we provide evidence that human observers can discriminate rotation rate with high precision. Weber fractions in the present study ranged from 0.13 to 0.21. In addition, our observers could make rotation rate discriminations independently of trial to trial variations in TTP and the direction of MID.

4. Experiment 3

4.1. Purpose

In Experiments 1 and 2 observers made judgments of TTP, direction of MID and rotation rate in separate trial blocks. In everyday life, however, e.g., when hitting a baseball, it would be necessary to make all three judgments during each delivery of the ball. The purpose of Experiment 3 was to measure thresholds for discrimination of TTP, direction of MID and rate of rotation when the observer was making all three judgments on each trial.

4.2. Method

4.2.1. Apparatus and procedure

The apparatus and procedure were identical to that described for Experiment 2 except that the observer was given a response box with three pairs of buttons and was required to judge the TTP, direction of MID and rate of rotation on each trial. Each observer completed two experimental blocks (one for overspin and one for underspin) each comprised of three repeats of the 216 trials described for Experiment 2. For each of the three judgments we again plotted separate psychometric functions for TTP, β and $d\eta/dt$ and calculated Weber fractions as described for Experiment 1. Each threshold estimate was based on 108 data points.

4.2.2. Observers

The same four observers completed Experiment 3.

4.3. Results and discussion

Table 6 shows Weber fractions for TTP, direction of MID and rotation rate judgments, respectively. A comparison with the results from Experiment 2 (Tables 3–5) shows that the Weber fractions were little, if at all, increased when judgment were made simultaneously as compared to individual judgments. To statistically compare thresholds in Experiments 2 and 3 we performed pairwise t-tests for each judgment. The difference between discrimination thresholds in the condition where observers made a single judgment on each trial and the condition where all three judgments were made simultaneously were not significant for TTP, direction of MID and rotation rate ($p > 0.1$ for all). We conclude that attentional resources are not appreciably more loaded

Table 6
Discrimination thresholds for the TTP, direction of MID and rotation rate judgment in Experiment 3

Observer	TTP, over	TTP, under	β, over	β, under	$d\eta/dt$, over	$d\eta/dt$, under
1	0.12	0.15	0.14	0.15	0.16	0.17
2	0.17	0.19	0.23	0.24	0.23	0.25
3	0.19	0.22	0.15	0.15	0.19	0.16
4	0.11	0.13	0.16	0.18	0.18	0.19

when performing three as compared with a single judgment.

5. General discussion

5.1. Independent and parallel judgments about an approaching object?

To successfully intercept an approaching object (e.g., hitting or catching a baseball) it has been proposed that the observer needs to judge *where* the approaching object will be at some future instant and *when* it will be there (Lee, Young, Reddish, Lough, & Clayton, 1983; Tyldesley & Whiting, 1975).[4] It is has been proposed that these judgments are made independently of each other and of other sources of visual information (Regan, 1982). Furthermore, judgments about *where* and *when* must be made either in parallel or in very quick succession: major league batters make the decision to swing at a pitch when the ball in about 20 ft (6 m) from the plate (Breen, 1967), and for a 90 mph (40 m/s) fastball this is only about 0.3 s after the pitcher releases the ball. Most previous research on the use of monocular information in interception has investigated judgments of *where* and *when* separately (i.e., observers were required to judge either *where* or *when*) and did not include some retinal image variables that are commonly present for approaching objects in the everyday world (e.g., ball rotation). Therefore, whether the independent judgment criterion is met for approaching objects is not clear from previous research. To address these limitations, in the present study we varied TTP, direction of MID, rotation rate and directly compared performance when observers made three as compared with only one judgment after each stimulus presentation.

Are the stimulus variables associated with an approaching object judged independently? Results from the present study suggest that these variables are not judged completely independently. Our observers could discriminate TTP effectively independently of task-irrelevant variables such as the rotation rate, rotation direction and total change in object size, but could not completely unconfound TTP and the direction of MID. Instead our observers showed a "hitting the head bias" where TTP was perceived to be shorter for objects on a collision course with the head compared to objects that would miss the head.

When our observers judged the direction of MID in the vertical plane they also showed only partial independence in judgments: Although discriminations of the direction of MID were effectively independent of simultaneous variations in TTP they were influenced by ball rotation. These observers showed a bias towards overestimating the value of β (i.e., perceiving the ball as headed more towards the ground, see Fig. 3) when the simulated ball traveled with overspin as compared to simulated underspin. Furthermore, the magnitude of this bias increased as spin rate was increased. These errors in judgment were in the correct direction to allow for the change in the trajectory of a real spinning baseball that would be caused by the Magnus Effect. The results of the Magnus Effect on the trajectory of a spinning ball are familiar to even the novice players of table tennis or tennis and most particularly to the incompetent golfer. In a future study we plan to investigate whether this misperception of trajectory caused by rotation is still observed when the rotation actually effects the direction of MID, i.e., when the Magnus Effect is included in the simulation.

Rotation rate was the only discrimination that could be made effectively independently of other retinal image variables. Our observers could make fine discriminations of rotation rate (Weber fractions of 0.14–0.21) that were not effectively influenced by variations in TTP and variations in the direction of MID. To our knowledge this is the first report of the ability of human observers to make rotation judgments for an approaching object.

5.2. Could a lack of judgment independence be advantageous in some situations?

The ability to judge stimulus variables that are relevant for the control of action independently of other variables is an important requirement of successful performance in fast ball sports (e.g., baseball, tennis and cricket). For a simple example consider the judgment of direction of MID and color. If a tennis player could not judge the direction of MID independently of color then he/she might misjudge the trajectory of the ball if a white ball was substituted for a yellow one. However, due to the limited range of conditions, in some sports there is a correlation between retinal image variables that is considerably greater than in situations with a wider range of stimulus variables. For example, the rate of expansion alone cannot in general be used to estimate TTC because TTC is determined by both angular size and rate of expansion (i.e., Eq. (3)). But in sports such as baseball and soccer the physical size of ball is constant so that TTC and rate of expansion are perfectly correlated [see (Smith, Flach, Dittman, & Stanard, 2001) for an example of this type of range effect]. Another example is the relationship between rotation direction, direction of MID and TTP in baseball. A fastball (that has a short TTP) travels with a component of under-spin while a curveball (that has a longer TTP and different direction of MID) travels with a component of over-spin (Williams & Underwood, 1970). Previous research has shown that experienced baseball batters are sensitive to rotation direction (Burroughs, 1984) and can use it to adjust the timing of their swing (Gray, 2002) whereas novice players do not use this dependency between rotation direction and pitch type. Might skill-level in fast ball sports be related to judgment independence?

In a previous study on judgment independence in highly skilled pilots flying telemetry-tracked jet aircraft it was

[4] See Peper, Bootsma, Mestre, and Bakker (1994) for an alternative proposal.

reported that inter-individual differences in the performance of some flying tasks correlated with the independence of processing changing-size and frontal plane motion (Kruk & Regan, 1983). This finding brings out the point that, while a correlation between visual variables (here trajectory with overspin versus underspin) can render a learned dependence of judgments advantageous within a highly constrained situation, in less constrained situations it is judgment independence that is advantageous.

5.3. Would binocular information increase judgment independence?

There are binocular sources of retinal information that previous research has shown can be used to accurately judge absolute TTC (Gray & Regan, 1998) and the absolute direction of MID (Gray et al., 2006) that we did not simulate in the present study. We have previously shown that in some situations where observers cannot judge TTC independently of task-irrelevant variables (e.g., angular size or rate of expansion) on the basis of monocular information alone, independent judgments are exhibited when binocular cues to TTC are added (Gray & Regan, 1998, 2000a). Therefore, we might also expect that the addition of binocular information would improve the ability of our observers to unconfound TTP, direction of MID and rotation rate and we plan to test this in a future study.

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